A Distributed Equivalent Magnetic Circuit Approach for Large Scale Superconducting Wind Turbine Generators

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This paper proposes an effective design and analysis tool integrating the equivalent magnetic circuit model into distributed magnetic computation technique for the superconducting wind turbine generators considering electromagnetic coupling spatial structure, nonlinear magnetic material, superconducting coils properties, and etc. these exist two most common ways for design and analysis of electrical machines. One is the magnetic equivalent circuit which is used at the initial design stage without considering the dimension size and resulting in the gross electrical parameters of electrical machine. The other is the FEM which is utilized in most cases but is time-consuming at computing process and regenerated on the condition of any alterable structure. A distributed computing technique based on magnetic equivalent circuit is divided into three sub models: the first is stator magnetic computing part with nonlinear magnetic material and MgB_2 superconducting armature coils; the second is rotor part with superconducting coils and linear non-magnetic material; the third is interface including pole-teeth coupling and air gap. Besides, the 10-MW-class superconducting wind turbine generator, whose rotor adopts MgB_2 superconducting field coils and Al alloy pole while whose stator employs silicon steel sheets and cooper windings, is designed via the distributed equivalent magnetic circuit approach and then verified with FEA. The comparisons validate the effectiveness of the proposed model.

***Index Terms*—Distributed computing, Finite element analysis (FEA), magnetic equivalent circuit, Superconducting wind turbine generator, Superconducting coils**

I. Introduction

Superconducting electric machines employs the characteristics of high efficiency, high power density, and low loss resulting in industrial applications such as large-scale power wind turbine, large-scale vessel propulsion, High-torque linear motor and other related areas whose requirement is of less dimensioning and higher power density.

For offshore wind farm, a new concept of high power density, lightweight, low-cost and reliable wind turbine generator for offshore wind farm applications using superconducting technologies is a viable solution. However, equivalent magnetic circuit method does not have the access to accurately acquire the magnetic flux saturation and machine characteristics especially for the machines of complicated structure or high accuracy, while complicated computation course of FEA makes it a tough task to reduce the calculation time to develop a new concept of large-scale superconducting wind turbine generators.

The magnesium diboride (MgB_2) wires possess several important merits: low cost, simple machining technique and operating in a cryogen-free cooling system compared to low temperature superconducting material. So large scale SC wind turbine Generators with MgB2 becomes very promising candidate for wind turbines.

Distributed computing is a common technique for massive electromagnetic field calculation solver with the developing of the microprocessor technique and the emergency of super-computer. One large-scale process can be divided into several sub block which can be computed separately and interactive via the relative interfaces.

A distributed computing based on equivalent magnetic circuit (DEMC) employing rapid computing speed and detailed magnetic model is utilized to solve the large-scale SC Wind Turbine Generators. In the paper three sub models comprising DEMC is introduced to design and analyze the 10-mw-class salient pole wind turbine SC generators with MgB_2 (SPWTSG) magnetic field.

II. Design Properties and Analysis Model of SPWTSG

A. A New Concept Structure of SPWTSG

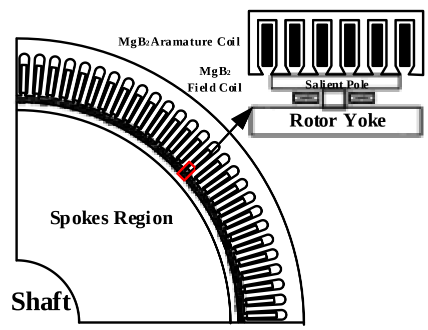

Fig.1. Cross-section Schematic Model of one-fourth SPWTSG

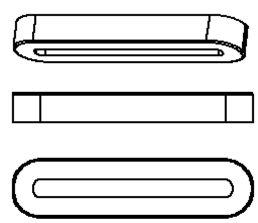

Fig.2. Sketch of a race-track superconducting coils with MgB2

Fig. 1 describes the cross-section schematic model of the quarter conceptual structure for SPWTSG of high power density, lightweight, and high efficiency. In addition, the race-track-shaped MgB2 coils is depicted in the Fig.2. Structure Specifications of SPWTSG

B. Sub Models of DEMC

stator sub model employs the passive multiport magnetic circuit model where the *ith* segment is composed of two reluctances in parallel: the leakage reluctance $R_{m.l.i}$ and the reluctance through silicon steel $R_{m.s.i}$, all the N_s segments in serials compose the whole stator equivalent magnetic circuit combining with interface sub model via the node MMF F_i and magnetic flux ϕ_i. The *ith* slot of this sub model is described in the following equations.

$$\begin{bmatrix} 1 & 0 & 0 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} F_{i-1} \\ F_i \\ F_{i+1} \end{bmatrix} = \begin{bmatrix} F_{i-2} \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} \phi_{i-1} \\ \phi_i \\ \phi_{i+1} \end{bmatrix} \begin{bmatrix} R_{m.i-1} & 0 & 0 \\ 0 & R_{m.i} & 0 \\ 0 & 0 & R_{m.i+1} \end{bmatrix}$$

Where $R_{m.i} = \dfrac{1}{\dfrac{1}{R_{m.s.i}} + \dfrac{1}{R_{m.l.i}}}$, $i \subset [2, \mathrm{N}_s - 1]$ and N_s is the number of slots.

Interface sub model is made of teeth and air gap, and the teeth shape provides the transmission channel which influences greatly the magnetic reluctance according to pole-teeth coupling. So the equivalent magnetic circuit is a parallel of several teeth magnetic reluctance $R_{m.t.i.j}$ which is variable with the spatial topology and distance from the superconducting coils and the air gap reluctance $R_{m.a.i.j}$ .according to the design experiments, the number of slots per pole per phase is three. This sub model between *jth* pole and *ith* slot is shown.

$$\begin{bmatrix} F_j \\ F_j \\ F_j \end{bmatrix} - \begin{bmatrix} F_{i-1} \\ F_i \\ F_{i+1} \end{bmatrix} = \begin{bmatrix} \phi_{i-1} \\ \phi_i \\ \phi_{i+1} \end{bmatrix} \begin{bmatrix} R_{m.l.i-1.j} + R_{m.a.i-1.j} & 0 & 0 \\ 0 & R_{m.l.i.j} + R_{m.a.i.j} & 0 \\ 0 & 0 & R_{m.l.i+1.j} + R_{m.a.i+1.j} \end{bmatrix}$$

Rotor sub model employs the active multiport magnet circuit model including the SC coil with MgB_2 and rotor core. The SC coil is excited by the direct current and superconducting wires possess the zero-resistance and anti-magnetism characteristics. So the MMF F_j and magnetic flux ϕ_j is calculated by the Ampere circuital theorem. So the magnets of SC coils can simply be modeled as an equivalent MMF:

$$F_j = NI$$

And inner reluctance

$$R_{m.j} = \frac{h_j}{\mu_r \mu_0 l_j w_j}$$

Where h_j, l_j and w_j are the SC magnet thickness, length and width, respectively.

So the *jth* pole of this sub model is given.

$$\begin{bmatrix} 1 & 0 & 0 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} F_{j-1} \\ F_j \\ F_{j+1} \end{bmatrix} = \begin{bmatrix} F_{j-2} \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} \phi_{j-1} \\ \phi_j \\ \phi_{j+1} \end{bmatrix} \begin{bmatrix} R_{m.j-1} & R_{m.j} & 0 \\ 0 & R_{m.j} & R_{m.j+1} \\ 0 & 0 & R_{m.j+1} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \phi_{j+2} * R_{m.j+2} \end{bmatrix}$$

C. A Distributed Equivalent Magnetic Circuit Computing Technique

The specific software procedure is described in the following Fig.3.

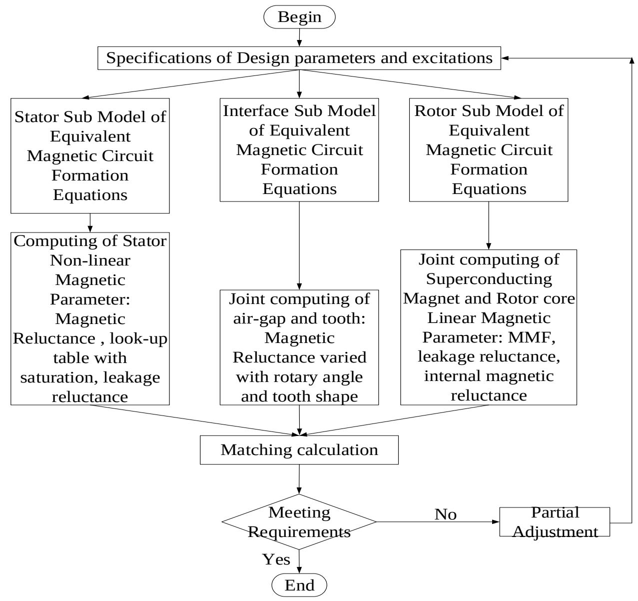

Fig.3. Software Procedure of Distributed Computing

III. Static Calculation and Analysis

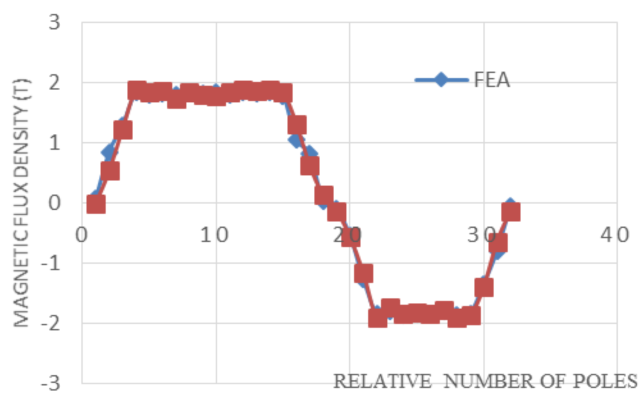

Fig.4. Quarter of air gap magnetic density by DEMC and FEA

IV. Conclusion

A DEMC has been proposed to calculate the basic design parameters of 10-MW-Class Direct-drive Salient-Pole Superconducting Synchronous Wind Turbine Generators considering the magnetic saturation, pole-teeth magnetic coupling, and SC coil magnet calculation. A distributed computing model, of which each sub-model can operated mutually dependent and interactive, was developed to improve the accuracy and save the computing time. The results via DEME is verified by the FEA.References

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